

LONG-PISTON HYDRAULIC MACHINES

RELATED APPLICATIONS

[1] This application is a Continuation-In-Part of U.S. copending parent Application No. 10/229,407, filed 28 August 2002, which application is hereby incorporated by reference.

TECHNICAL FIELD

[2] This invention relates to hydraulic pump/motor machines that have elongated pistons reciprocating in cylinders and, more particularly, to a system for lubricating such pistons while maintaining contact between the heads of such pistons and the swash-plate of the pump/motor.

BACKGROUND

[3] Hydraulic pumps and motors are well known and widely used, having reciprocating pistons mounted in respective cylinders formed in a cylinder block and positioned circumferentially at a first radial distance about the rotational axis of a drive element. Many of these pump/motor machines have variable displacement capabilities; and they are generally of two basic designs: (a) either the pistons reciprocate in a rotating cylinder block against a variably inclined, but otherwise fixed, swash-plate or (b) the pistons reciprocate in a fixed cylinder block against a variably inclined and rotating swash-plate that is generally split to include a non-rotating (but nutating) wobbler that slides upon the surface of a rotating (and nutating) rotor. While the invention herein is applicable to both of these designs, it is particularly

appropriate for, and is described herein as, an improvement in the latter type of machine.

[4] While hydraulic machines with fixed cylinder blocks can be built much lighter and smaller than the machines that must support and protect heavy rotating cylinder blocks, the mounting and support of the swash-plate wobblers has always been a major problem. For high-pressure/high-speed service, the wobbler must be supported in a manner that allows the relative motion between the non-rotating pistons and the wobbler to follow varying non-circular paths. Also, such fixed-cylinder-block machines have heretofore used a "dog-bone" extension rod (i.e., a rod with two spherical ends) to interconnect one end of each piston with the flat surface of the nutating-but-not-rotating wobbler. One spherical end of the dog bone is pivotally mounted into the head end of the piston, while the other spherical end is usually covered by a pivotally-mounted conventional "shoe" element that must be held at all times against the swash-plate wobbler. These just-mentioned elements greatly increase the complexity and cost of building the rotating swash-plates of these machines.

[5] Dog-bone rods are also sometimes used to interconnect one end of each piston with the inclined (but not rotating) swash-plates of hydraulic machines having rotating cylinder blocks. However, more often this latter type of machine omits such dog-bones, using instead elongated pistons, each having a spherical head at one end (again, usually covered by a pivotally-mounted conventional shoe element) that effectively contacts the non-rotating flat surface of the swash-plate. Such elongated pistons are designed so that a significant portion of the axial cylindrical body of each piston remains supported by the walls of its respective cylinder at all times during even the maximum stroke of

the piston. This additional support for such elongated pistons is designed to assure minimal lateral displacement of each spherical piston head as it slides over the inclined-but-not-rotating swash-plate when the pistons rotate with their cylinder block.

[6] Generally, these elongated pistons are primarily lubricated by "blow-by", i.e., that portion of the high-pressure fluid that is forced between the walls of each cylinder and the outer circumference of each piston body as the reciprocating piston drives or is driven by high-pressure fluid. Such blow-by provides good lubrication only if tolerances permit the flow of sufficient fluid between the walls of the cylinder and the long cylindrical body of the piston, and blow-by sufficient to assure good lubrication often negatively affects the volumetric efficiency of the pump or motor machine. For instance, a 10 cubic inch machine can use as much as 4 gallons of fluid per minute for blow-by. While smaller tolerances can often be used to reduce blow-by, the reduction of such tolerances is limited by the need for adequate lubrication.

[7] The invention disclosed below is directed to improving the volumetric efficiency of such elongated-piston machines while, at the same time, assuring (a) appropriate lubrication of the pistons and (b) simplification of the apparatus used to maintain contact between the pistons and the swash-plate.

SUMMARY OF THE INVENTION

[8] The invention is disclosed on two different hydraulic machines. Both have the preferred format of fixed cylinder blocks and rotating/nutating swash-plates. [However, persons skilled in the art will appreciate that the invention is equally applicable to hydraulic

machines with rotating cylinder blocks and swash-plates that do not rotate with the drive elements of the machines.] Each disclosed machine can operate as either a pump or a motor. One has a swash-plate that, while rotating at all times with the drive element of the machine, is fixed at a predetermined inclined angle relative to the axis of the drive element so that the pistons move at a maximum predetermined stroke at all times. The swash-plate of the other disclosed machine has an inclination that can be varied throughout a range of angles in a manner well known in the art to control the stroke of the pistons throughout a range of movements up to a maximum in each direction.

[9] In each machine, each piston is elongated, having an axial cylindrical body portion that preferably is substantially as long as the axial length of the respective cylinder in which it reciprocates. Preferably, each piston also has a spherical head end that, by means of a conventionally pivoted shoe and relatively simple apparatus, is maintained in effective sliding contact with a flat face of the machine's swash-plate. The axial length of each cylindrical piston body is selected to assure minimal lateral displacement of the spherical first end of the piston at all times. Therefore, even when each piston is extended to its maximum stroke, that portion of the piston body which is still supported within its respective cylinder is sufficient to assure a minimal lateral displacement of the extended spherical end of the piston when it is in sliding contact with the rotating/nutating flat face of the swash-plate.

[10] According to the invention, each cylinder formed within the cylinder blocks of each machine is provided with a respective lubricating channel formed in the cylindrical wall of each cylinder. This

lubricating channel is positioned so that at all times during reciprocation of the piston within its respective cylinder, each respective lubricating channel remains substantially closed by the axial cylindrical body of the piston during its entire stroke. Preferably, each respective lubricating channel is formed circumferentially and radially transects each cylinder.

[11] Also formed in the fixed cylinder block of each machine is a plurality of further passageways that interconnect each of the just-described lubricating channels. The interconnection of all of the lubricating channels, one to another, forms a single, continuous lubricating passageway in the cylinder block. This continuous lubricating passageway is formed entirely within the cylinder block, preferably transecting each cylinder and being centered circumferentially at substantially the same radial distance as the cylinders are centered about the rotational axis of the drive element.

[12] [NOTE: To facilitate explanation of the invention, each piston is described as having an axial cylindrical body portion and a spherical head end, while each respective cylinder has a valve end and an open head portion beyond which the spherical head end of each piston extends at all times.] In the preferred embodiments disclosed, the continuous lubricating passageway just described above is not connected by either fluid "input" or fluid "output" passageways but instead is substantially closed off by the cylindrical body portions of the pistons at all times during operation of the machine. During operation, this lubricating passageway almost instantly fills with initial blow-by of high-pressure fluid that enters at the valve end of each cylinder and then passes between the walls of each cylinder and the outer circumference of the body portion of each driven piston. This

blow-by effectively maintains high pressure within the continuous lubricating passageway at all times. A plurality of sealing members, each located respectively near the open end of each cylinder, provides a relatively tight seal for substantially eliminating blow-by between the body portion of each piston and the open head portion of each respective cylinder, thereby allowing the escape of only minimal blow-by from this lubricating passageway past the open end of the cylinders.

[13] Nonetheless, the lubricating fluid in this closed continuous lubricating passageway moves constantly as the result of the ever-changing pressures in each of the respective cylinders as the pistons reciprocate. That is, as the pressure in each cylinder is reduced to low pressure on the return stroke of each piston, the high-pressure fluid in the otherwise closed lubricating passageway is again driven between the walls of each cylinder and the outer circumference of the body of each piston into the valve end of each cylinder experiencing such pressure reduction. However, this secondary blow-by is not "lost", i.e., it does not return to the sump to be replenished into the closed loop hydraulic system by the charge pump. Instead, this secondary blow-by is immediately returned to the closed loop without requiring the use of a charge pump, and the closed continuous lubricating passageway is immediately replenished by the entrance of a similar flow of high-pressure blow-by from the valve end of each cylinder experiencing increased pressure.

[14] This just-described lubricating passageway provides appropriate lubrication to the high-speed reciprocation of the pistons while substantially reducing blow-by. During successful operation of commercial prototypes built according to the invention, blow-by was reduced by 90%. That is, the blow-by experienced by conventional

commercial hydraulic machines of comparable specifications generally ranges between 4-5 gallons per minute, while the blow-by experienced by the invention's prototypes ranges between 0.5-0.7 gallons per minute, thereby remarkably increasing the volumetric efficiency of the invention's hydraulic machines.

[15] As indicated above, fixed-cylinder-block hydraulic machines can be built smaller and lighter than conventional rotating block hydraulic machines having similar specifications. As a result of the improved lubrication of the elongated pistons, the disclosed invention makes it possible to use these smaller and lighter designs to meet the high-speed/high-pressure specifications required for automotive use.

[16] Further, special attention is called to the invention's significantly simplified support assemblies for the variable rotating swash-plates of the invention's disclosed hydraulic machines. Each of the invention's support assemblies disclosed herein (a) omits dog-bones that normally are mounted between the outer end of each piston and the nutating-only wobbler portion of a conventional rotating/nutating swash-plate but (b) also omits the nutating-only wobbler portion of a conventional rotating/nutating swash-plate. Instead, a conventional shoe is mounted directly to the spherical head of each piston and is maintained in effective sliding contact with the flat face of the swash-plate's rotor portion by means of a minimal spring bias sufficient to maintain such effective sliding contact in the absence of hydraulic pressure at the valve ends of the pump's cylinders.

[17] Two simplified support mechanisms are disclosed: The first simplified support mechanism comprises a unique hold-down plate assembly biased by a coil spring positioned circumferentially about the rotational axis of the pump's drive element. The invention's second

support mechanism is even simpler, comprising nothing more than a conventional shoe mounted directly to the spherical head of each piston, with the minimal bias being supplied by a plurality of springs, each spring being positioned respectively between the body portion of each respective piston and the valve end of each respective cylinder. While the second support mechanism is a little more difficult to assemble than the first, the latter is considerably simpler, lighter, and cheaper to manufacture.

[18] The important changes introduced by this invention not only provide hydraulic machines that are lighter and smaller than conventional machines having similar specifications but, further, provide machines with greater volumetric efficiency while reducing the weight and size of the machines as well as the cost of manufacture and simplifying assembly.

DRAWINGS

[19] FIG. 1 is a partially schematic and cross-sectional view of a hydraulic machine with a fixed cylinder block and a rotating/nutating swash-plate having a fixed angle of inclination, showing the invention incorporated in the cylinder block and at the piston/swash-plate interface.

[20] FIG. 2 is a partially schematic and cross-sectional view of the fixed cylinder block of the hydraulic machines of FIGS. 1 and 3 taken along the plane 2-2 with parts being omitted for clarity.

[21] FIG. 3 is a partially schematic and cross-sectional view of a hydraulic machine with a fixed cylinder block and a rotating/nutating swash-plate having a variable angle of inclination, again showing the

invention incorporated in the cylinder block and at the piston/swash-plate interface.

[22] FIGS. 4A and 4B are partially schematic and cross-sectional views of the swash-plate and piston shoe hold-down assembly disclosed in FIGS. 1 and 3 when the swash plate is inclined at $+25^\circ$, with parts removed for clarity, showing relative positions of the head ends of the pistons, shoes, and special washers, as well as the spring-biased hold-down element that biases each sliding shoe against the flat face of the swash-plate; the view in FIG. 4A is taken in the plane 4A-4A of FIG. 3 in the direction of the arrows, while the view in FIG. 4B is taken in the plane 4B-4B of FIG. 4A.

[23] FIGS. 5A and 5B, 6A and 6B, and 7A and 7B are, respectively, views of the same parts illustrated in FIGS. 4A and 4B when the swash-plate is operating at three other inclinations, namely, at $+15^\circ$, 0° , and -25° .

[24] FIG. 8 is an enlarged, partial, schematic and cross-sectional view of only a single cylinder and piston for another hydraulic machine similar to those shown in FIGS. 1 and 3 but showing a more simplified second embodiment of a spring-biased hold-down assembly for the invention's piston shoes.

DETAILED DESCRIPTION

[25] The operation of hydraulic machines of the type to which the invention may be added is well known. Therefore, such operation will not be described in detail.

Hydraulic Motor

[26] Referring to FIG. 1, hydraulic motor 10 includes a fixed cylinder block 12 having a plurality of cylinders 14 (only one shown) in which a respective plurality of mating pistons 16 reciprocates between the retracted position of piston 16 and the extended position of piston 16'. Each piston has a spherical head 18 that is mounted on a neck 20 at one end of an elongated axial cylindrical body portion 22 that, in the preferred embodiments shown, is substantially as long as the length of each respective cylinder 14.

[27] Each spherical end 18 fits within a respective shoe 24 that slides over a flat face 26 formed on the surface of a rotor 28 that, in turn, is fixed to a drive element, namely, shaft 30 of the machine. Shaft 30 is supported on bearings within a bore 31 in the center of cylinder block 12. Flat face 26 of fixed rotor 28 is inclined at a predetermined maximum angle (e.g., 25°) to the axis 32 of drive shaft 30, being supported by an appropriate thrust bearing assembly 35.

[28] A modular valve assembly 33, which is bolted as a cap on the left end of cylinder block 12, includes a plurality of spool valves 34 (only one shown) that regulates the delivery of fluid into and out the cylinders 14. As indicated above, each of the machines disclosed can be operated as either a pump or as a motor. For this description of a preferred embodiment, the fixed-angle swash-plate machine shown in FIG. 1 is being operated as a motor. Therefore, during the first half of each revolution of drive shaft 30, high-pressure fluid from inlet 36 enters the valve end of each respective cylinder 14 through a port 37 to drive each respective piston from its retracted position to its fully extended position; and during the second half of each revolution, lower pressure fluid is withdrawn from each respective cylinder through port

37 and fluid outlet 39 as each piston returns to its fully retracted position.

[29] In a manner well known in the art, fluid inlet 36 and outlet 39 are preferably connected through appropriate "closed loop" piping to a mating hydraulic pump (e.g., pump 110 shown in FIG. 3 and discussed below) so that, at all times, fluid pressure biases spherical ends 18 and respective shoes 24 against flat face 26. The serial extension and retraction of each respective piston causes rotor 28 to rotate, thereby driving shaft 30. Flat face 26 is fixed at the maximum angle of inclination so that, when the flow rate of hydraulic fluid being circulated in the closed loop through inlet 36 and outlet 39 is relatively small, pistons 16 reciprocate relatively slowly, resulting in a relatively slow rotation of drive shaft 30. However, as the flow rates of fluid circulation in the closed loop increase, the reciprocation of the pistons increases accordingly and so does the speed of rotation of drive shaft 30. When operated at automotive speeds or pressures (e.g., up to 4000 rpm or 4000 psi), lubrication of the pistons becomes critical, and blow-by losses can also greatly increase. Cylinder block 12 is modified by the invention to address such lubrication needs and to reduce such blow-by losses.

[30] Referring now to both FIGS. 1 and 2, the cylindrical wall of each cylinder 14 is transected radially by a respective lubricating channel 40 formed circumferentially therein. A plurality of passageways 42 interconnect all lubricating channels 40 to form a continuous lubricating passageway in cylinder block 12. Each respective lubricating channel 40 is substantially closed by the axial cylindrical body 22 of each respective piston 16 during the entire stroke of each piston. That is, the outer circumference of each cylindrical body 22

acts as a wall that encloses each respective lubricating channel 40 at all times. Thus, even when pistons 16 are reciprocating through maximum strokes, the continuous lubricating passageway interconnecting all lubricating channels 40 remains substantially closed off. Continuous lubricating passageway 40, 42 is simply and economically formed within cylinder block 12 as can be best appreciated from the schematic illustration in FIG. 2 in which the relative size of the fluid channels and connecting passageways has been exaggerated for clarification.

[31] During operation of hydraulic motor 10, all interconnected lubricating channels 40 are filled almost instantly by blow-by of high-pressure fluid from inlet 36 entering each cylinder 14 through port 37 and being forced between the walls of the cylinders and the outer circumference of each piston 16. Loss of lubricating fluid from each lubricating channel 40 is restricted by a surrounding seal 44 located near the open end of each cylinder 14. Nonetheless, the lubricating fluid in this closed continuous lubricating passageway of lubricating channels 40 flows moderately but continuously as the result of "secondary" blow-by in response to piston motion and to the changing pressures in each half-cycle of rotation of drive shaft 30 as the pistons reciprocate. As the pressure in each cylinder 14 is reduced to low pressure on the return stroke of each piston 16, the higher pressure fluid in otherwise closed lubricating passageway 40, 42 is again driven between the walls of each cylinder 14 and the outer circumference of body portion 22 of each piston 16 into the valve end of each cylinder 14 experiencing such pressure reduction.

[32] However, special attention of persons skilled in the art is called to the fact that this just-mentioned secondary blow-by back into

cylinder 14 is not "lost". Instead, it is immediately returned to the well-known closed hydraulic fluid loop that interconnects the pump and motor. Further, this secondary blow-by does not return to a sump and, therefore, does not have to be replenished into the closed loop hydraulic system by a charge pump. Finally, closed continuous lubricating passageway 40, 42 is immediately replenished by the entrance of a similar flow of high-pressure blow-by from the valve end of each cylinder experiencing increased pressure.

[33] As mentioned above, there is minimal blow-by loss from closed continuous lubricating passageway 42 that interconnects all lubricating channels 40. That is, there may be a minimal fluid flow that leaks from this closed continuous lubricating passageway past the seals 44 at the end of each cylinder 14. However, any such minimal blow-by is instantly replenished by a similar flow of blow-by entering around the opposite end of each piston 16.

[34] The just-described lubrication arrangement is not only remarkably simple, but it also permits a similar simplification of the pinion/swash-plate interface apparatus of the hydraulic machine to further reduce the cost of manufacture and operation.

[35] To complete the description of hydraulic motor 10, the pinion/swash-plate interface apparatus shown in FIG. 1 comprises only (a) rotor 28 mounted on drive shaft 30 using conventional needle and thrust bearings and (b) a simple spring-biased hold-down assembly for maintaining piston shoes 24 in constant contact with the rotating and nutating flat surface 26 of rotor 28. [Note: Two embodiments of the invention's simplified pinion/swash-plate interface assemblies are described in greater detail in a separate section below.]

[36] The first embodiment of the invention's hold-down assembly, as shown in FIG. 1, includes a coil spring 50 that is positioned about shaft 30 and received in an appropriate crevice 52 formed in cylinder block 12 circumferentially about axis 32. Spring 50 biases a hold-down element 54 that is also positioned circumferentially about shaft 30 and axis 32. Hold-down element 54 is provided with a plurality of openings, each of which surrounds the neck 20 of a respective piston 16. A respective special washer 56 is positioned between hold-down element 54 and each piston shoe 24. Each washer 56 has an extension 58 that contacts the outer circumference of a respective shoe 24 to maintain the shoe in contact with flat face 26 of rotor 28 at all times.

[37] The just-described hydraulic motor, with its remarkable simplification of both lubrication and the piston/swash-plate interface, is efficient, easy to manufacture, and economical to operate.

Variable Hydraulic Pump

[38] A second preferred embodiment of a hydraulic machine in accordance with the invention is illustrated in FIG. 3. A variable hydraulic pump 110 includes a modular fixed cylinder block 112 which is identical to cylinder block 12 of hydraulic motor 10 shown in FIG. 1 and described above. Cylinder block 112 has a plurality of cylinders 114 (only one shown) in which a respective plurality of mating pistons 116 reciprocates between the retracted position of piston 116 and variable extended positions (the maximum extension being shown in the position of piston 116'). Each piston has a spherical head 118 that is mounted on a neck 120 at one end of an elongated axial cylindrical body portion 122 that, in the preferred embodiment shown, is substantially as long as the length of each respective cylinder 114. Each spherical piston head 118 fits within a respective shoe 124 that slides over a flat face

126 formed on the surface of a rotor 128 that, as will be discussed in greater detail below, is pivotally attached to a drive element, namely, shaft 130 that is supported on bearings within a bore 131 in the center of cylinder block 112.

[39] In a manner similar to that explained above in regard to hydraulic motor 10, variable pump 110 is also provided with a modular valve assembly 133 that is bolted as a cap on the left end of modular cylinder block 112 and, similarly, includes a plurality of spool valves 134 (only one shown) that regulates the delivery of fluid into and out of cylinders 114.

[40] As indicated above, each of the machines disclosed can be operated as either a pump or as a motor. For the description of this preferred embodiment, the variable-angle swash-plate machine 110 shown in FIG. 3 is being operated as a pump, and drive shaft 130 is driven by a prime mover (not shown), e.g., the engine of a vehicle. Therefore, during the one-half of each revolution of drive shaft 130, lower pressure fluid is drawn into each respective cylinder 114 entering a port 137 from a "closed loop" of circulating hydraulic fluid through inlet 136 as each piston 116 is moved to an extended position. During the next half of each revolution, the driving of each respective piston 116 back to its fully retracted position directs high-pressure fluid from port 137 into the closed hydraulic loop through outlet 139. The high-pressure fluid is then delivered through appropriate closed loop piping (not shown) to a mating hydraulic motor, e.g., motor 10 discussed above, causing the pistons of the mating motor to move at a speed that varies with the volume (gallons per minute) of high-pressure fluid being delivered in a manner well known in the art.

[41] Once again referring to modular cylinder block 112, it is constructed identical to cylinder block 12 which has already been described. That is, the cylindrical wall of each cylinder 114 is transected radially by a respective lubricating channel 40' formed circumferentially therein. A plurality of passageways 42' interconnects all lubricating channels 40' to form a continuous lubricating passageway in cylinder block 112. A cross section of cylinder block 112 taken in the plane 2-2 looks exactly as the cross-sectional view of cylinder block 12 in FIG. 2.

[42] In effect, almost all of the discussion above relating to the invention's continuous lubricating passageway 40, 42 with reference to the apparatus of hydraulic motor 10 shown in FIGS. 1 and 2 applies equally to the operation of continuous lubricating passageway 40', 42' in cylinder block 112 of hydraulic pump 110 shown in FIG. 3, including the minimization of loss of lubricating fluid from each lubricating channel 40' by a surrounding seal 144 located near the open end of each cylinder 114. Similarly, the flow of lubricating fluid in closed continuous lubricating passageway 40', 42' is moderate but continuous as the result of "secondary" blow-by in response to piston motion and to the changing pressures in each half-cycle of rotation of drive shaft 130 as the pistons reciprocate. Of course, as is different in pump 110, lower fluid pressure is present in each cylinder 114 when each piston 116 is moving to an extended position, while the source of the high-pressure fluid that is forced between the walls of the cylinders and the outer circumference of each piston 116 occurs as each piston 116 is being driven from its extended position to its fully retracted position by the rotation of drive shaft 130 by the prime mover (not shown).

[43] However, once again special attention of persons skilled in the art is called to the fact that this just-mentioned secondary blow-by back into each cylinder 114 is not "lost". Instead, it is immediately returned to the well-known closed hydraulic fluid loop that interconnects the pump and motor. That is, this secondary blow-by does not return to a sump and, therefore, does not have to be replenished into the closed loop hydraulic system by a charge pump. Also, while there may be a minimal fluid flow that leaks from closed continuous lubricating passageway 40', 42' past the seals 144 at the end of each cylinder 114, any such minimal blow-by is instantly replenished by a similar flow of blow-by entering around the opposite end of each piston 116 experiencing increased pressure.

[44] As discussed in the preamble above, the invention permits the machine's swash-plate apparatus to be simplified by (a) the omission of the dog-bones that normally are mounted between the outer end of each piston and a nutating-only wobbler portion of a conventional rotating/nutating swash-plate and (b) the omission of the wobbler portion itself as well as the apparatus conventionally required for mounting the non-rotating wobbler to the rotating/nutating rotor portion of the swash-plate.

[45] Rotor 128 is pivotally mounted to drive shaft 130 about an axis 129 that is perpendicular to axis 132. Therefore, while rotor 128 rotates with drive shaft 130, its angle of inclination relative to axis 130 can be varied from 0° (i.e., perpendicular) to $\pm 25^\circ$. In FIG. 3, rotor 128 is inclined at $+25^\circ$. This variable inclination is controlled as follows: The pivoting of rotor 128 about axis 129 is determined by the position of a sliding collar 180 that surrounds drive shaft 130 and is movable axially relative thereto. A control-link 182 connects collar 180 with

rotor 128 so that movement of collar 180 axially over the surface of drive shaft 130 causes rotor 128 to pivot about axis 129. For instance, as collar 128 is moved to the right in FIG. 3, the inclination of rotor 128 varies throughout a continuum from the +25° inclination shown, back to 0° (i.e., perpendicular), and then to -25°.

[46] The axial movement of collar 180 is controlled by the fingers 184 of a yoke 186 as yoke 186 is rotated about the axis of a yoke shaft 190 by articulation of a yoke control arm 188. Yoke 186 is actuated by a conventional linear servo-mechanism (not shown) connected to the bottom of yoke arm 188. In this preferred embodiment, while the remainder of the elements of yoke 186 are all enclosed within a modular swash-plate housing 192 and yoke shaft 190 is supported in bearings fixed to housing 192, yoke control arm 188 is positioned external of housing 192.

[47] It will also be noted that swash-plate rotor 128 is balanced by a shadow-link 194 that is substantially identical to control-link 182 and is similarly connected to collar 180 but at a location on exactly the opposite side of collar 180.

Piston Shoe Hold-Down Assemblies

[48] Fluid pressure constantly biases pistons 116 in the direction of rotor 128, and a thrust plate 198 is provided to carry that load. However, at the speeds of operation required for automotive use (e.g., 4000 rpm), additional bias loading is necessary to assure constant contact between piston shoes 124 and flat surface 126 of rotor 128. In view of the invention's omission of conventional dog-bones and omission of the conventional wobbler as well as its required mounting assembly, the variable hydraulic machines of this invention are able to

provide such additional bias by using either of two simple spring-biased hold-down assemblies, the first being similar to that already described above in regard to hydraulic motor 10 in FIG. 1.

[49] (a) Hold-Down Assembly with Single-Spring Bias

[50] The following description of the invention's first embodiment for a hold-down assembly continues to refer to FIG. 3, but reference is now also made (a) to FIG. 4A, which shows an enlarged view taken in the plane 4A-4A of FIG. 3 when viewed in the direction of the arrows, and (b) to FIG. 4B, which shows an enlargement of the same view of shown in FIG. 1 with parts removed for clarity.

[51] The hold-down assembly for pump 110 includes a coil spring 150 that is positioned about shaft 130 and received in an appropriate crevice 152 formed in cylinder block 112 circumferentially about axis 132. Coil spring 150 biases a hold-down element 154 that is also positioned circumferentially about shaft 130 and axis 132. Hold-down element 154 is provided with a plurality of circular openings 160, each of which surrounds the neck 120 of a respective piston 116. A plurality of special washers 156 is positioned, respectively, between hold-down element 154 and each piston shoe 124. Each washer 156 has an extension 158 that contacts the outer circumference of a respective shoe 124 to maintain the shoe in contact with flat face 126 of rotor 128 at all times.

[52] The positions of the just-described parts of the swash-plate and piston shoe hold-down assembly change relative to each other as the inclination of rotor 128 is altered during machine operation. These changes in relative position are illustrated at various inclinations of rotor 128, namely, at +25°, in FIGS. 4A and 4B; at +15° in FIGS. 5A and

5B; at 0° in FIGS. 6A and 6B; and at -25°, in FIGS. 7A and 7B. [NOTE: Persons skilled in the art will appreciate that each piston shoe 124 has a conventional pressure-balancing cavity centered on the flat surface of shoe 124 that contacts flat face 126 of rotor 128, and that each respective shoe cavity is connected through an appropriate shoe channel 162 and piston channel 164 to assure that fluid pressure present at the shoe/rotor interface is equivalent at all times with fluid pressure at the head of each piston 116. Since piston channel 164 passes through the center of spherical head 118 of each piston 116, the position of channel 164 can be used to facilitate appreciation of the relative movements of the various parts of the hold-down assembly.]

[53] Referring to the relative position of these parts at the 0° inclination shown in FIGS. 6A and 6B, each piston channel 164 (at the center of each spherical head 118 of each piston 116) has the same radial position relative to each respective circular opening 160 in hold-down element 154. As can be seen from the views in the other illustrated inclinations of swash-plate rotor 128, at all inclinations other than 0°, the relative radial position of each piston channel 164 is different for each opening 160, and the relative positions of each special washer 156 is also different.

[54] It must be appreciated that, at each of these illustrated swash-plate inclinations, the different relative positions at each of the nine openings 160 are themselves constantly changing as rotor 128 rotates and nutates through one complete revolution at each of these inclinations. For instance, at the 25° inclination shown in FIG. 4A, if during each revolution of rotor 128, one were to watch the movement occurring through only the opening 160 at the top (i.e., at 12:00

o'clock) of hold-down element 154, the relative position of the parts viewed in the top opening 160 would serially change to match the relative positions shown in each of the other eight openings 160.

[55] That is, at inclinations other than 0° (e.g., at -25° shown in FIG. 7A), during each revolution of rotor 128, each special washer 156 slips over the surface of hold-down element 154 as, simultaneously, each shoe 124 slips over the flat face 126 of rotor 128; and each of these parts changes relative to its own opening 160 through each of the various positions that can be seen in each of the other eight openings 160. These relative motions are largest at $\pm 25^\circ$; and each follows a cyclical path (that appears to trace a lemniscate, i.e., a "figure-eight") that varies in size with the angular inclinations of swash-plate rotor 128 and the horizontal position of each piston 116 in fixed cylinder block 112.

[56] Therefore, to assure proper contact between each respective shoe 124 and flat face 126 of rotor 128, in preferred embodiments, a size is selected for the boundaries of each opening 160 so that the borders of opening 160 remain in contact with more than one-half of the surface of each special washer 156 at all times during each revolution of rotor 128 and for all inclinations of rotor 128, as can be seen from the relative positions of special washers 156 and the borders of each of the openings 160 in each of the drawings from FIG. 4A through FIG. 7A. As can be seen from the drawings, a circular border is preferred for each opening 160.

[57] Finally, attention is called to the suggested manufacture of each shoe 124 and its respective mating special washer 156 using reinforced thermoplastic resin materials. These mating parts can also be combined to form a single thermoplastic shoe/washer combination,

with the shoe portion being manufactured so that it is formed about the spherical head 118 of each piston 16', 22. Similarly, the cost and complexity of thrust bearing assembly 35 can be significantly reduced by the use of reinforced thermoplastic resins.

[58] (b) Hold-Down Assembly with Multiple-Spring Bias

[59] The second embodiment of the invention's hold-down assembly, while slightly more difficult to assemble, is considerably simpler and less expensive. This second embodiment is shown schematically in FIG. 8 in an enlarged, partial, and cross-sectional view of a single piston of a further hydraulic machine 210 according to the invention. Piston 216 is positioned in modular fixed cylinder block 212 within cylinder 214, the latter being transected radially by a respective lubricating channel 40'' formed circumferentially therein. In the same manner as described in relation to the other hydraulic machines already detailed above, lubricating channel 40'' is interconnected with similar channels in the machine's other cylinders by a plurality of passageways that forms a continuous lubricating passageway in cylinder block 212; and, similarly, a surrounding seal 244 is located near the open end of each cylinder 214 to minimize the loss of lubricating fluid from each lubricating channel 40''.

[60] The only difference between fixed cylinder block 212 and the modular cylinder blocks disclosed in FIGS. 1 and 3 is that fixed cylinder block 212 includes neither a large axially circumferential coil spring nor an axially circumferential crevice for holding the same.

[61] While not shown, the modular fixed cylinder block 212 of hydraulic machine 210 can be connected to either a modular fixed-angle swash-plate assembly (as shown in FIG. 1) or a modular variable-

angle swash-plate assembly (as shown in FIG. 3); but in either case, hydraulic machine 210 provides a much simpler hold-down assembly. Specifically, the hold-down assembly of this embodiment comprises only a respective conventional piston shoe 224 for each piston 216 in combination with only a respective coil spring 250, the latter also being associated with each respective piston 216.

[62] Each piston shoe 224 is similar to the conventional shoes shown in the first hold-down assembly just discussed above and, similarly, is mounted on the spherical head 218 of piston 216 to slide over the flat face 226 formed on the surface of the machine's swash-plate rotor 228 in a manner similar to that explained above. Each coil spring 250 is, respectively, seated circumferentially about hydraulic valve port 237 at the valve end of each respective cylinder 214 and positioned within the body portion of each respective piston 216.

[63] Again, in the manner just explained above, each shoe 224 slips over flat face 226 of rotor 228 with a lemniscate motion that varies in size with the horizontal position of each piston 216 and the inclination of rotor 228 relative to axis 230. During normal operation of hydraulic machine 210, shoes 224 are maintained in contact with flat face 226 of the swash-plate by hydraulic pressure. Therefore, the spring bias provided by coil springs 250 is only minimal but still sufficient to maintain effective sliding contact between each shoe 224 and flat face 226 in the absence of hydraulic pressure at the valve end of each respective cylinder 214.

[64] It has been found that the just-described minimal bias of springs 250 not only facilitates assembly but is also sufficient to prevent entrapment of tiny dirt and metal detritus encountered during assembly and occasioned by wear. Further, special attention is again

called to the fact that this second embodiment provides this necessary function with only a few very inexpensive parts.

[65] The just-described pump/motor as well as the invention's other hydraulic machines described earlier, all provide both lubrication and a piston/swash-plate interface that are remarkably simple and relatively inexpensive to manufacture and provide further economies by reducing the number of parts required for efficient operation and increasing volumetric efficiency.